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AUTONOMOUS WIND-GENERATED ELECTRICITY USED FOR WATER PUMPING

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ABSTRACT

A wind turbine with variable voltage, variable frequency electrical output was selected to power a stand-alone pumping system. The AC system was selected because AC motors, in multiple kW sizes, can be more practical than DC motors. A wind turbine which produces electricity has a lower overall efficiency than a mechanical system, but offers more flexibility in adapting to varying load sizes and in site selection.

A permanent magnet alternator wind energy conversion system, designed to operate with a rotor speed from 70 to 150 r/min, was operated in the laboratory. The frequency of the output varied from 30 to 65 Hz, while the voltage changed from 85 to 250 V resulting in a V/f ratio from 2.6 to 3.3 with various loads. The alternator, with a maximum rated output of 9 kW, provided power to resistive loads or induction motor loads.

The tests revealed that standard three-phase, AC induction motors will pump water when operating at 30 Hz and 85 V. A motor temperature rise of 40°C above ambient was not exceeded when power was supplied by the alternator. At rotor speeds of 120 and 150 r/min, peak motor efficiency equaled the efficiency achieved with conventional power. System efficiencies with load matching were equivalent to those obtained with utility power even though the V/f ratio was below that calculated from the motor's nameplate. The system was then operated in the field in windspeeds of 3.5 m/s or greater. We found this permanent magnet alternator capable of providing power of sufficient quality to satisfactorily pump water in a stand-alone system.

NOMENCLATURE

AC = Alternating Current
Cp = Coefficient of Performance
DC = Direct Current
NEMA = National Electrical Manufacturer's Association
V/f = Voltage to Frequency
WECS = Wind Energy Conversion Systems

INTRODUCTION

The operation of a wind turbine without interconnection to the electric utility has numerous applications for agriculture. The load may be located where power distribution from a utility may not be practical or economical. A WECS producing mechanical power can be more efficient, but the load matching capabilities and flexibility of an electrical system can be more practical.

Two prevalent methods for producing electricity using a wind turbine are with an induction generator or an alternator connected to a line-commutated inverter (1,2). The induction generator with a speed increaser has a small amount of slip but operates essentially at a fixed rotor speed with a variable tip-speed ratio (blade tip-speed/windspeed). Cp of a wind turbine is a function of tip-speed ratio, therefore, an induction generator will have a variable Cp as the windspeed fluctuates. The line-commutated inverter, which converts the alternator output to utility quality power, is a substantial addition to the cost of a WECS. Both methods require excitation from the utility and produce utility compatible electricity.

Satisfactory performance from an induction motor is generally obtained over a range of plus or minus 10% from rated voltage and plus or minus 5% from rated frequency (3). The torque developed by the motor is approximately proportional to the square of the voltage and inversely proportional to the square of the frequency. Reduced torque may result in failure of the motor to start, accelerate, or attain rated speed. Less than rated voltage with constant frequency may additionally affect the power factor, efficiency, and operating temperature of the induction motor. Actual motor speed typically changes less than 5% between no-load and full-load. Induction motors in multiple kilowatt sizes are more cost effective in comparison to DC motors.

A motor with a NEMA Class B insulation has a design life of 10,000 hours and is designed to have its insulation at a temperature no greater than 130°C at full-load (4). Higher motor temperatures than 130°C can degrade insulation and reduce motor life. An induction motor's efficiency will increase as its load is increased to its rated output. The selection of motor size is a compromise between motor life, efficiency, and cost.

The variation of voltage and frequency to a polyphase stator has been a method of speed control for ship propulsion motors (5). When changing frequency, it is necessary to change the applied voltage in the same manner and to the same extent in order to maintain the same degree of saturation and mutual air-gap flux density. If the V/f ratio is not maintained constant, the system will operate at a lower efficiency and may be subjected to overloads. The constant V/f ratio assures an almost constant-current operation for the motor and prevents thermal overload (6). A reduction in frequency will lower the synchronous speed and result in a decrease in motor speed which may not be acceptable for some applications. Johnson and Walker (7) reported on the successful simulated operation with variable voltage, variable frequency power of a 2.2-kW motor connected to a heat pump.

The rotational speed, voltage, and frequency of the output of a wind driven asynchronous alternator is proportional to the windspeed. The power available from the wind varies as the cube of the windspeed. The power required by a centrifugal or turbine pump is proportional to the cube of the rotational speed for the pump. The variable frequency output of the alternator will vary the speed of the pump, thus providing a good match between power required and power available.

DESCRIPTION OF EQUIPMENT

The commercially available WECS selected for the project was a Windworker 10, manufactured by Windworks Inc.[1] The variable-speed alternator produces a variable frequency, variable voltage, three-phase AC output. The three-bladed horizontal-axis machine with a swept area of 78.5 m^2 is rated at 9 kW in a 9 m/s wind and is its maximum power rating. Conventionally, the electrical output is connected to a line-commutated inverter which converts the output to power compatible with the utilities.

The speed of the alternator's rotor is regulated by varying the pitch of the blades. The blades are held in a feathered position at windspeeds below 3.5 m/s. Windspeeds at 3.5 m/s or greater produce a change in the blade pitch resulting in a rotor speed of 70 r/min or greater. The blades remain fixed in pitch as the windspeed and rotor speed increase to 150 r/min. As the alternator speed increases above 150 r/min, the blades will adjust to a lower attack angle to maintain a constant speed of 150 r/min.

[1] Mention of a product or tradename does not constitute a recommendation or endorsement for use by the USDA.

The wind turbine, with a direct-drive permanent magnet alternator, was tested in the laboratory by powering the alternator with a variable-speed motor. Resistive loads and induction motor loads were used to initially access the potential applications (8). Voltage, current, power, and frequency of the alternator output were monitored. A linear output of frequency between 30 to 65 Hz was observed for alternator speeds from 70 to 150 r/min.

Consultation with the manufacturer of the measuring transducers, Rochester Instrument Systems (RIS)[1], indicated that error would be greater than cited for voltage, current, and power measurements below 50 Hz. The accuracy of the transducers was monitored during the resistive load testing. The calculated power factor, PF = kW/(1.732 x V x I), was compared to a power factor of 1 for a resistive load. The accuracy of the transducers at 30 Hz resulted in a difference of 7% between kVA and kW and was reduced as the frequency increased to 60 Hz.

DESCRIPTION OF TESTS

Several combinations of resistive loads were tested with the voltage and frequency of a representative load shown in Fig. 1. The voltage varied from 210 V at 150 r/min to 110 V at 70 r/min. The maximum alternator output for all loads tested, measured at 150 r/min, was 9.2 kW.

Two three-phase motors rated at 5.6 kW and 7.6 kW, were individually operated with a variable load from a hydraulic pump. Further testing was conducted using 5.6-, 7.6-, and 12.6-kW motors driving a centrifugal pump.

The four pole induction motors were rated at 230 V and 1750 r/min. The motors, with Class B insulation and NEMA Design Code B, were designed for continuous operation with a service factor of 1.15. The 5.6-, 7.6-, and 12.6-kW motors had identical nameplate

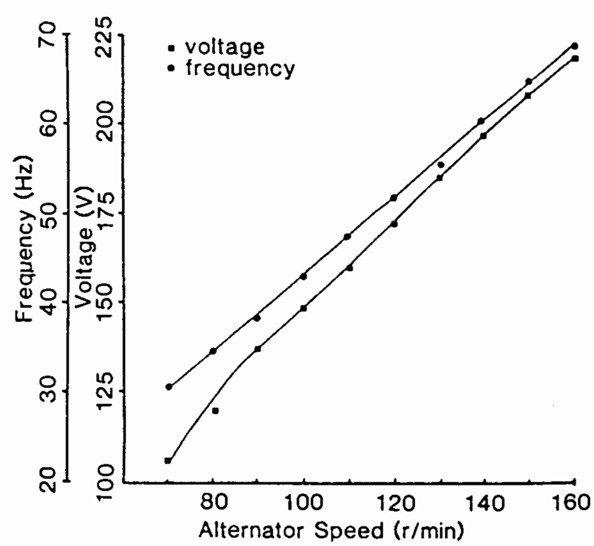

Fig. 1. Line voltage and frequency versus rotational speed of alternator for an equivalent 8 ohm resistive load.

information except for the current, which was 21, 26, and 42 A, respectively. The nameplate V/f ratio calculated from 230 V and 60 Hz was 3.8.

Baseline data for each test was established by operating a motor with power from the utility. The alternator was then driven at rotational speeds from 70 to 150 r/min to supply power to a motor.

RESULTS

The voltage from the alternator was lower than the motor's nameplate values of 230 V for all tests (Fig. 2). The balanced three-phase voltage ranged from 81 to 99 V at 70 r/min and 170 to 218 V at 150 r/min.

The V/f ratio was 3.3 with no load on the motors and dropped to 2.6 when a motor approached its breakdown torque. It was approximately the same for all the alternator speeds tested.

Figure 3 shows the effect of rotor speed on current and motor power output for the 5.6-kW motor. For a given power output, the alternator-driven motor drew a larger current than the utility powered motor. Current requirements were greater for the 7.6-kW versus the 5.6-kW motor at power outputs below 3 kW.

Motor temperatures were measured by the insertion of thermocouples adjacent to the windings. Figure 4 shows the temperature rise above ambient of the motors versus motor power output. The 5.6-kW motor had a temperature rise of 44°C when producing 5.6 kW with utility power. Higher temperatures were recorded for power outputs below 5.6 kW when power was supplied by the alternator. When the temperature rise was 40°C, a further increase in motor power output would result

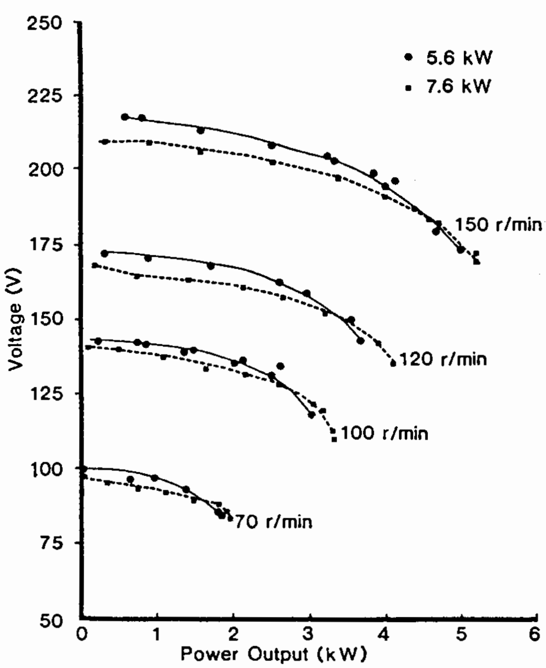

Fig. 2. Line voltage versus motor power output of 5.6-, 7.6-kW motors with electrical power from alternator.

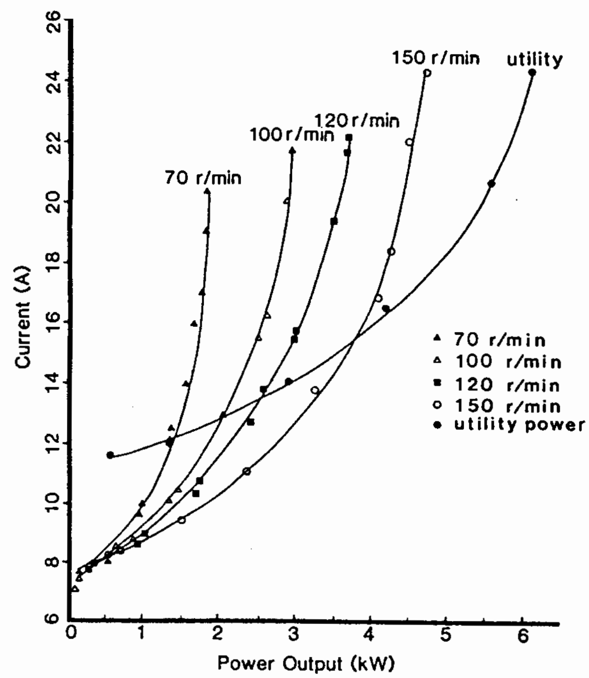

Fig. 3. Current versus motor power output of 5.6-kW motor with electrical power from utility and alternator.

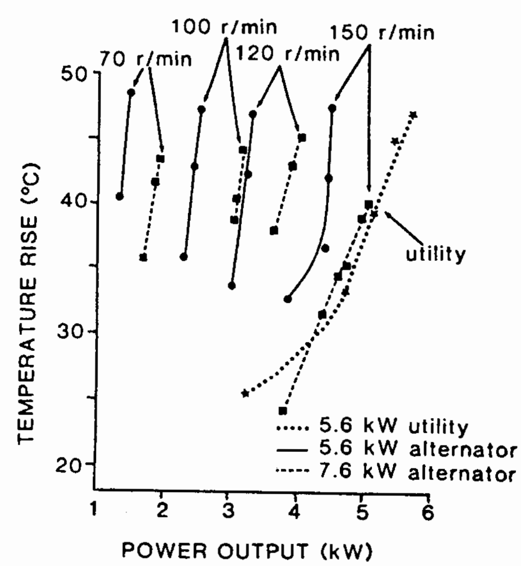

Fig. 4. Temperature rise above ambient versus motor power output for 5.6- and 7.6-kW motors with electrical power from the utility and alternator.

in a significantly increased temperature rise with alternator supplied power. The 7.6-kW motor had a cooler operating temperature than the 5.6-kW motor for a similar power output.

The motors with alternator supplied power attained peak efficiency below 5.6 kW. Figure 5 shows the 5.6-kW motor efficiency versus motor power output with the utility and various alternator speeds. As power output approaches 5.6 kW, the efficiency of the motor with the alternator dropped while the efficiency of the motor powered by the utility remained constant.

Efficiencies for the 5.6- and 7.6-kW motors are compared to their power output in Fig. 6. Peak efficiency is approximately the same for the two motor sizes, however, they occur at different power outputs.

Figure 7 compares motor speed with respect to torque. The synchronous speed of a motor is a function of frequency with the various alternator speeds being depicted by the distinct curves. The breakdown torque of the 5.6-kW motor ranged from 22 and 26 N-m for the alternator speeds from 70 to 150 r/min, respectively. The slip of the motor did not significantly change with the substitution of the 7.6-kW motor, but the torque did increase to a maximum of 28 N-m at 150 r/min.

A centrifugal pump was tested with various motors in the laboratory. Figure 8 is the pump curve for a Berkley Model B3ZRM[3], with motors powered by the utility or the alternator. Flow rates were from 14 to 133 m^3/hr, while the total dynamic head varied from 2 to 23 m.

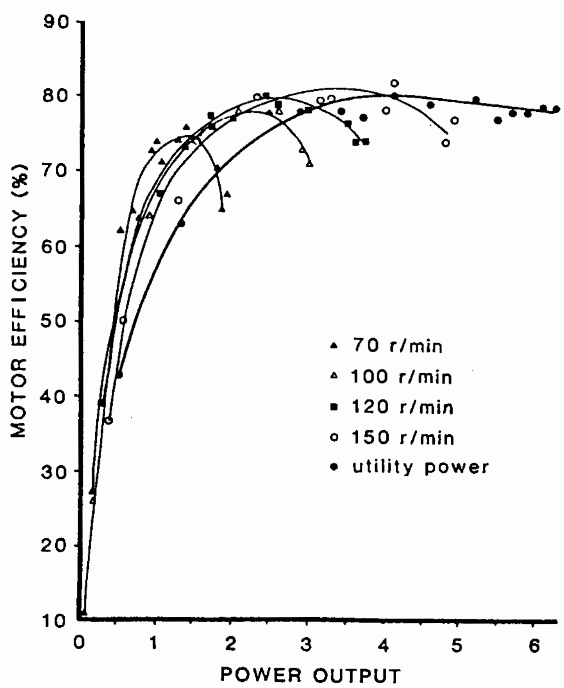

Fig. 5. Motor efficiency versus motor power output for a 5.6-kW motor with electric power from utility and alternator.

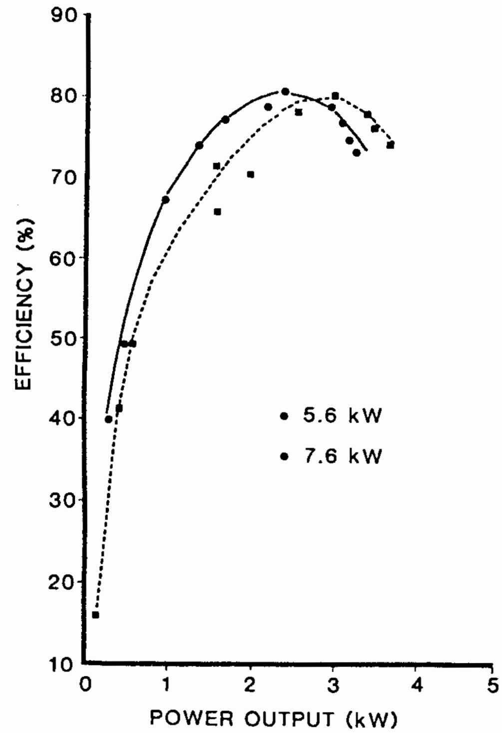

Fig. 6. Motor efficiency versus motor power output for 5.6- and 7.6-kW motors with alternator speed at 100 r/min.

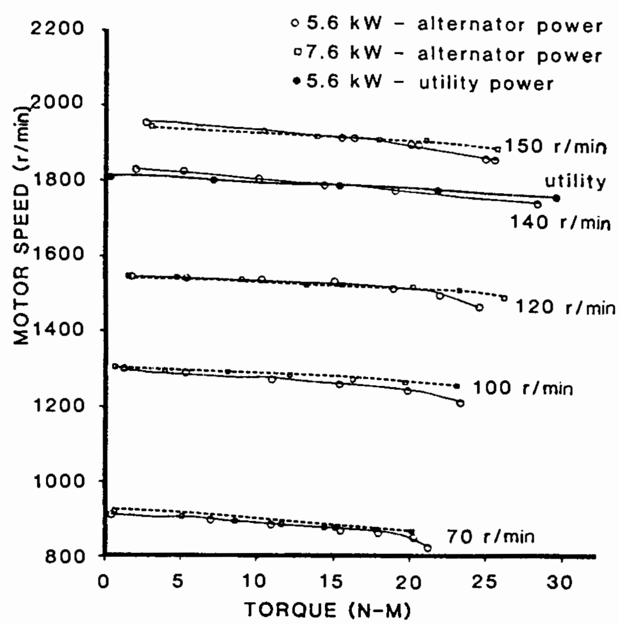

Fig. 7. Motor rotational speed in comparison to motor power output of 5.6- and 7.6-kW motors with electrical power from the utility and alternator.

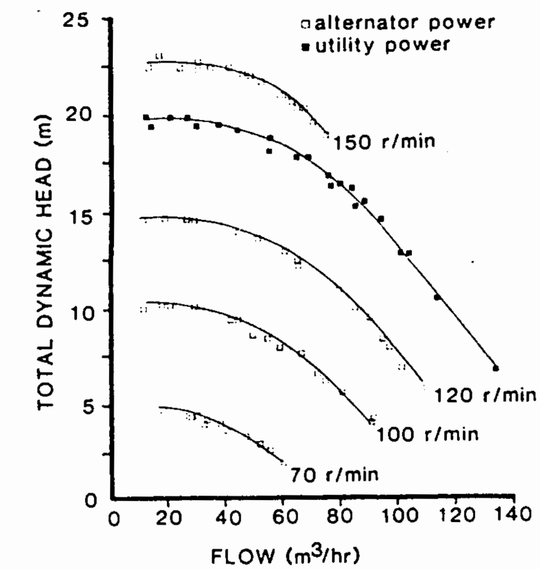

Fig. 8. Pump curves for centrifugal pump with 18 cm impeller and 7.6-kW motor for electrical power from utility and alternator.

Figure 9 shows the overall efficiency of the system, including motor and pump losses, with respect to the flowrate. The 7.6-kW motor and an 18 cm impeller were tested, with power to the motor from four alternator speeds and the utility. The efficiency increased with alternator speed resulting in a peak efficiency of 60% while the utility peak efficiency was 58%.

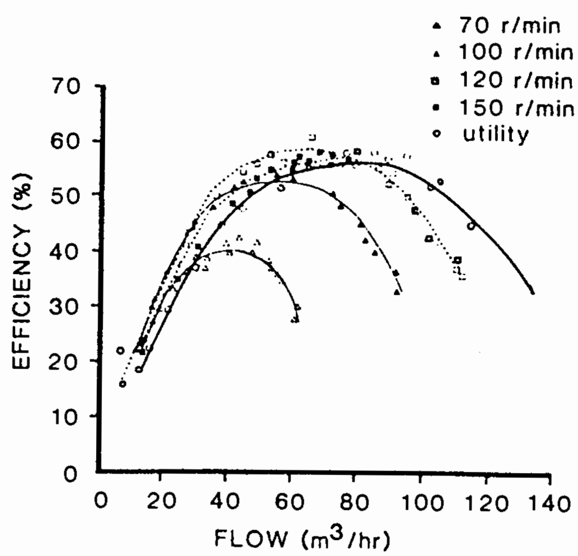

Fig. 9. Overall efficiency of centrifugal pump with 18 cm impeller and 7.6-kW motor for electrical power from utility and alternator.

The Windworker 10 was operated in the field where waterflow and power requirements of the pump were regulated to the torque limitations of the motor. As the windspeed changed, the rotational speed of the alternator varied between 70 and 150 r/min, with a corresponding change in the operation of the pump. The motor torque for the test was between 6 and 24 N-m while the water flow rates were from 21 to 50 m^3/hr. The characteristics of the pump are shown in Fig. 10. Pump efficiency varied from 50 to 61% while the motor power requirement of the system varied from 0.5 to 6 kW. A temperature rise of 40°C above ambient for the motor was not exceeded while the system was operated in the field.

The power curves for the Windworker 10 with the test load are shown in Fig. 11. The electrical power output of the alternator has been adjusted to a standard air density of 1.226 kg/m^3 with the maximum power limited by the physical constraint (motor torque) of the load (9). The maximum electrical power for the test was 5.9 kW at a windspeed of 8.5 m/s. Motor efficiencies ranged from 77 to 85% while the overall efficiency of the motor and pump was between 37 and 50%.

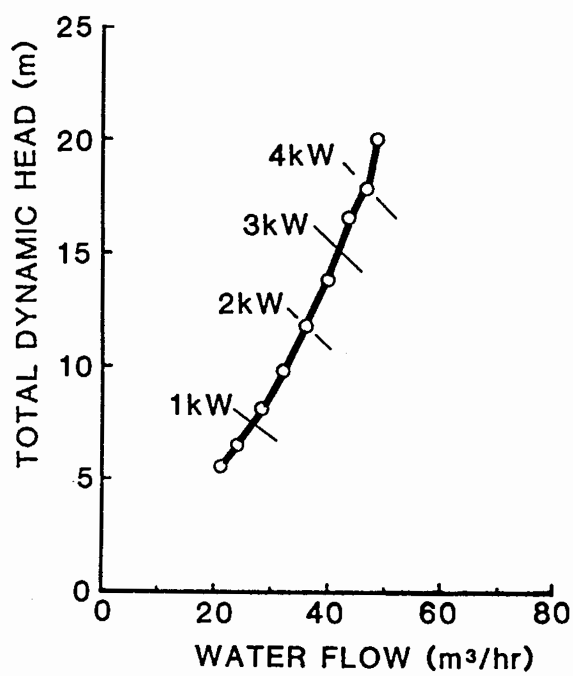

Fig. 10. Total dynamic head versus water flow for 7.6-kW motor with motor power requirements of centrifugal pump.

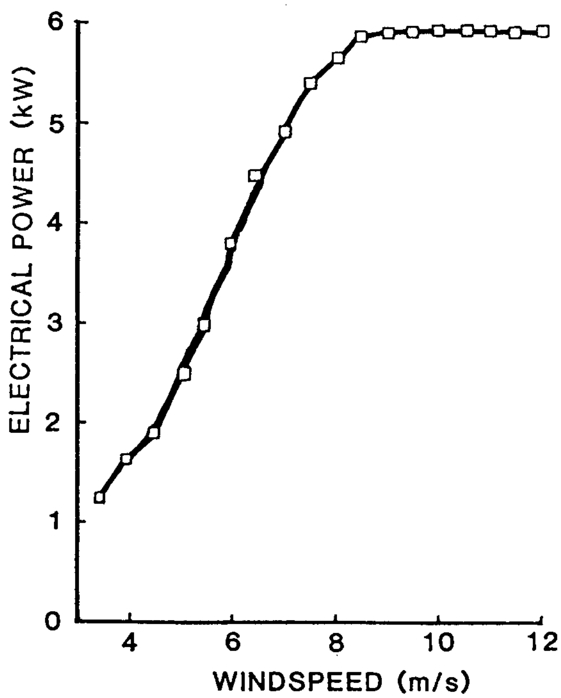

Fig. 11. Power curve of Windworker 10 with 7.6-kW motor and centrifugal pump, adjusted to standard air density.

SUMMARY AND CONCLUSIONS

The permanent magnet alternator, with output frequency from 30 to 65 Hz, provided power for resistive loads and induction motor loads. The induction motors, without significant increase in slip, had speeds from 800 to 1940 r/min. The voltage from the alternator ranged from 80 to 213 V, which was below the nameplate rating of 230 v. The lower voltage resulted in a larger current flow for similar power outputs when compared to operating with utility power. The V/f ratio varied from 2.6 to 3.3 which was below the nameplate of 3.8. Motor efficiency approached 80% with alternator power when the motors were parially loaded. At full motor output rating, the variable frequency and voltage input was not capable of maintaining a high efficiency. The operating temperature of the 5.6-kW motor was higher than normal and will result in a shorter life.

The operation of an autonomous system for irrigation does have several distinct requirements. The motor controller must be able to operate from the variable output of the alternator or utilize an external power source. The reduced voltage to the motor requires a load with low or moderate starting torque such as a centrifugal pump. The lower alternator voltage with reduced starting current does have comparable performance to a low voltage starter. An automated priming system is necessary for the pump to operate without manual assistance.

Induction motors will operate with lower torque when powered by a V/f ratio that is below the motor's nameplate. Peak motor efficiency occurs at a lower output than the motor rating. Lower than rated output for the motor is necessary to maintain an acceptable temperature rise.

It is desired that a variable voltage, variable frequency system operate at a constant V/f ratio, near that specified by the nameplate of the motor. However, it may not be practical to design a commercial WECS to power one specific load. We found this wind energy conversion system capable of providing power to satisfactorily pump water in an autonomous system.

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